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This MURI has been intended to address challenges of electronics technologies for wireless communication to dramatically enhance the low power and low noise characteristics. An interdisciplinary team with expertise spanning from the devices, circuits, components and systems has been assembled from researchers from UCLA and UC San Diego. A companion MURI program has also been executed at The University of Michigan with University of Colorado under the leadership of Professor George Haddad. Both of these electronics oriented programs are complementary rather than competitive. For instance, Michigan Program has placed emphasis on InP devices while UCLA/UCSD program studied GaAs type devices. Furthermore, these two electronics oriented MURI programs are complementary to another MURI program at Michigan that primarily studies the systems, modulation and coding aspects of low power communication. Nevertheless, both UCLA/UCSD and Michigan electronics programs contain some effort

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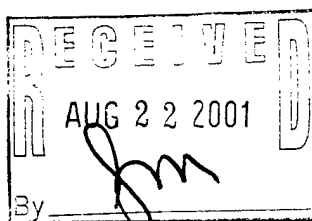
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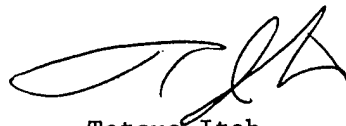
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Sincerely,



Tatsuo Itoh
Professor
University of California, Los Angeles

FINAL REPORT FOR MURI PROJECT

Low Power/Low Noise Electronics Technologies for Wireless Communications

**University of California, Los Angeles
University of California, San Diego**

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1. Introduction

This MURI has been intended to address challenges of electronics technologies for wireless communication to dramatically enhance the low power and low noise characteristics. An interdisciplinary team with expertise spanning from the devices, circuits, components and systems has been assembled from researchers from UCLA and UC San Diego. A companion MURI program has also been executed at The University of Michigan with University of Colorado under the leadership of Professor George Haddad. Both of these electronics oriented programs are complementary rather than competitive. For instance, Michigan program has placed emphasis on InP devices while UCLA/UCSD program studied GaAs type devices. Furthermore, these two electronics oriented MURI programs are complementary to another MURI program at Michigan that primarily studies the systems, modulation and coding aspects of low power communication. Nevertheless, both UCLA/UCSD and Michigan electronics programs contain some effort on the system and coding issues.

One of the most significant accomplishments in the area of technology transfer is our successful completion of a book entitled **RE Technologies for Low Power Wireless Communications** being printed at this writing by Wiley Interscience. The investigators on the MURI projects at UCLA/UCSD and University of Michigan have written this monograph book. It is considered that this book is an integral part of this final report. Since the technical accomplishments for the past 5 years in the life of these MURI projects are provided in details in this book, the present report provides technical accomplishments in the last segment of the 5-year period. This book is provided under separate cover as a supplement to this report as soon as the book copies are available.

2. Technical Achievements

(1) Multicarrier Direct-Sequence CDMA

Multicarrier (MC) direct-sequence (DS) code division multiple access (CDMA) has been proposed as an alternative design for the next-generation mobile communications. The available frequency spectrum is divided into M equiwidth frequency bands, where M is the number of subcarriers, and is typically much less than the processing gain. Neither orthogonality among carriers nor a contiguous spectrum are required.

One of the key problems with MC DS-CDMA systems is that both intermodulation (IM) distortion and harmonic (HM) distortion occur because of nonlinear amplification, since the input waveform to the power amplifier is the sum of multiple RF signals. Therefore, the design of MC DS systems with an IM suppression capability, and the evaluation of their performance, are key technical issues for MC DS-CDMA.

In one component of our research, we focused on interference suppression techniques at the receiver, where a coded MC minimum mean-squared error (MMSE) transceiver was used to combat both

multiple access interference (MAI) and IM distortion, the latter being introduced by a nonlinear power amplifier at the transmitter. A frequency-selective Rayleigh fading channel is decomposed into M frequency-nonselective channels, based on the channel coherence bandwidth. The transmitter employs linear convolutional codes of rate $1/M$. The M coded symbols are serial-to-parallel converted, and those symbols modulate M different DS-CDMA waveforms in parallel. The receiver provides a full correlation with the corresponding PN code for each subcarrier, and an MMSE filter is used after each correlator. The new system is shown to effectively combat intermodulation distortion in the presence of multiple-access interference.

(2) GaAs HBT with GaInNAs Base Region

GaAs HBTs are the devices of choice to implement power amplifiers in numerous wireless transmitters. To improve their power efficiency and their temperature stability, particularly with low battery voltage, it is important to reduce the V_{be} turn-on voltage. This can be accomplished by changing the bandgap of the material used as the base of the transistor. We have investigated the use of GaInNAs for the base layers of the devices. The addition of nitrogen together with indium to the GaAs base allows decreasing the bandgap while maintaining lattice-match to the GaAs substrate. We have demonstrated devices with turn-on voltage reduction of 0.2V, a record amount. We have investigated tradeoffs of N concentration and current gain and device speed. In collaboration with Kopin Corporation, materials have been grown which exhibit current gain in excess of 100, negligible change in f_t , and have significant V_{be} reductions (more than 0.1V). These materials are promising for insertion into manufacturing (providing improved performance with no change in subsequent processing).

(3) Tunnel collector GaAs-based HBT

A further improvement in GaAs HBT efficiency can be obtained by reducing the offset and knee voltages of the transistors, and eliminating the storage of minority carriers during saturated operation. Both these advantages can be obtained in principle with a suitable blocking layer for holes at the base-collector junction. We have explored layers of wide bandgap semiconductor (GaInP) located at the base-collector junction, to accomplish this. We found that to eliminate the unwanted blockage for electrons, two designs could be used. In one case, the GaInP layers can be made sufficiently thin that electrons can tunnel through them. A collector-up architecture further assists in reducing electron blockage, due to the asymmetric properties of the GaInP/GaAs interface. We have also demonstrated that the barrier to electrons can be reduced by the addition of nitrogen to the GaInP blocking layer, which reduces the conduction band offset without affecting the valence band offset energy.

(4) 1.8V LOW FLICKER NOISE RF AGC AND MIXER IMPLEMENTED WITH A NOVEL FOUR-TERMINAL HBT (FHBT)

We have recently observed that the current gain of AlGaAs/GaAs HBTs can be externally

modulated by biasing a Schottky electrode that contacts the emitter passivation ledge directly [1]. This observation leads to possible designs of RF AGCs and mixers within a single Four-terminal HBT (FHBT). Currently, most AGCs and mixers are designed based on a Gilbert cell structure. A recent discovery indicates that the current gain of AlGaAs/GaAs HBTs can be externally modulated by biasing a Schottky electrode that contacts the emitter passivation ledge directly. This discovery leads to possible implementations of complex RF AGC (automatic-gain-control) and signal mixing functions within a 4-terminal HBT (FHBT) at relatively low power supply voltages (down to $V_C=1.8V$). The low voltage operation has been extremely difficult for the conventional Gilbert-cell AGC and mixer design based on regular 3-terminal HBTs. The demonstrated FHBT AGC achieves 24dB gain control up to 6GHz. The FHBT mixer shows 7dB conversion gain and -12.5dBm IIP3 without emitter or base degeneration. The flicker noise of FHBTs is measured to be 3dB better than conventional HBTs fabricated on the same wafer. An empirical formula is proposed to predict the flicker noise of FHBTs under different bias conditions. Excellent flicker noise performance makes FHBT a promising candidate for advanced direct conversion transceiver circuit applications.

Conventional Gilbert Cell mixer design requires stacked stages and is particularly difficult to operate at low supply voltages. The presented FHBT RF AGC and mixer employ only one stage and a single transistor. It depends on the control of the emitter ledge potential within the device itself to realize the required circuit functions. Therefore, the FHBT AGC and mixer are uniquely suitable for low voltage operations. The measurement at $V_C=1.8V$ shows that the FHBT AGC offers very extensive gain control (>24dB) up to 6GHz and the FHBT mixer provides 7dB conversion gain and -12.5dBm in IIP3 without degenerating the device. Further study of FHBTs indicates that the flicker noise can be reduced if the ledge electrode is biased at a higher voltage than that of the base [2], i.e., it is possible to reduce the flicker noise by draining the electron-hole recombination current through the ledge electrode instead of the base. It is crucial to minimize the flicker noise in voltage controlled oscillator (VCO) and mixer designs for achieving high spectrum purity with low noise skirts in modern communication systems. The flicker noise is also a major issue in designing advanced direct-conversion transceivers that are capable of handling wide channel bandwidth with simple circuit architectures. [3] Since the flicker noise is a physical nature associated with semiconductor devices, it has been difficult to control the phase noise of HBTs through conventional 3-terminal device design and typical manufacturing processes. Our invention of FHBT opens new avenues in HBT device design to achieve low flicker noise RF oscillator and mixer functions at low supply voltages (down to 1.8V).

(5) Dynamic Supply Voltage Amplifier

The Dynamic Supply Voltage Amplifier (or Envelope Tracking Amplifier) is an architecture which permits maintaining high power efficiency under conditions where the output power level varies significantly (such as occurs in wireless transmitters with

spectrally efficient modulation). In prior years we demonstrated that a dc-dc converter employing high switching frequency could be used in conjunction with the amplifiers, in a way that could be implemented in small size and would permit rapid voltage modulation. More recently, we have studied an inherent nonlinearity mechanism in such amplifiers (if used with imperfect output transistors) and demonstrated that the nonlinearity could be countered by analog predistortion, or preferably, by digital predistortion. We demonstrated that the digital control approach cannot only provide the predistortion, it can lead to improved control over the power supply voltage (by implementing an optimal algorithm and by providing frequency equalization) to optimize efficiency.

(6) Doherty Amplifier

An alternative architecture that maintains high efficiency over a wide range of output powers is the Doherty Amplifier. The main amplifier operates with a high load impedance, and resulting high efficiency, at low power levels. At higher power, the auxiliary amplifier turns on, and in doing so changes the load impedance experienced by the main amplifier to avoid hard saturation. In traditional Doherty amplifiers, the range of power over which high efficiency can be obtained is 5-6dB. We have designed Doherty amplifiers in which high efficiency can be maintained over a power backoff range of 10-12 dB, making these amplifiers much more suitable for modern communications signals. We demonstrated a Doherty amplifier using GaAs HBTs, which maintains efficiency of at least 39% at 12 dB backoff from P1dB. To maintain linearity over the entire power range, it is critical to maintain proper bias conditions for the two amplifiers, as well as to provide an appropriate phase and amplitude relationship between the two input signals. We have begun to explore a DSP-controlled Doherty architecture, in which input signals (with appropriate predistortion) and bias voltages are established by the DSP.

(7) LINC Amplifier

If the output transistor of a power amplifier is used in switching-mode, the efficiency can be very high, since the transistor dissipates little power in its "OFF" state or in its "ON" state. In this program we demonstrated a current-mode class D amplifier employing GaAs MESFETs which achieves a power-added efficiency of 76% at 1GHz. Class E amplifiers also can achieve very high efficiency. Such amplifiers, however, are not capable of reproducing signals with time-varying envelope; the output power level is controlled by the power supply voltage. The switching-mode amplifiers can be used, however, in more complex architectures such as the LInear amplification with Nonlinear Components, or LINC amplifier. In modern implementations, DSP is used to form the Signal Component Separator (SCS), which derives from the input signal two separate signals that have constant envelope (but time varying phase) such that when the signals are summed, the appropriate output waveform (with time-varying envelope) is recovered, as a result of constructive or destructive interference. For the practical implementation, the two amplifiers in the two channels must be very accurately matched (typically 0.5 dB amplitude matching and 0.3 degree phase matching). These specifications are extremely difficult to

meet in open loop fashion. We have developed a DSP-based approach to calibrate the system, and derive appropriate signal distortions to be introduced into the two channel inputs to maintain high accuracy in the overall output. Simple calibration signals are inserted into the amplifier. A receiver is used to sample the output and derive correction factors for the signals in the two paths. A sequence of calibration steps converges rapidly to the desired result. Techniques that operate in foreground (during a calibration cycle) or in background (continuously during amplifier operation) have been demonstrated.

(8) Band-pass Delta Sigma Transmitter

An additional approach to employ switching-mode amplifiers for signals with time-varying envelope is the Class S amplifier, widely used for audio power amplification. To generate suitable waveforms, pulse-width modulation can be used. This requires a pulse repetition rate substantially ($>10\times$) higher than the desired output center frequency. The amplifier output is passed through a series filter that removes the excess quantization noise generated during the modulation process. The power associated with the undesired out-of-band spectral components must be reflected, rather than absorbed in the filter, to preserve high efficiency. This approach is difficult to use directly at microwave frequencies, because of the need for very high pulse repetition rates and very tightly controlled pulse widths. We have investigated amplifiers using the band-pass delta-sigma algorithm to generate digital signals that encode the analog signals of interest. The modulated output consists of a single bit digital data stream. The clock rate can be chosen to not very much higher than the center frequency of interest (typically $4\times$). The bandwidth of interest, however, must be a relatively small fraction of the center frequency and clock rate, such that a high effective "oversampling ratio" is maintained. Here the oversampling ratio is the ratio of the clock rate to the signal bandwidth. The unavoidable extraneous signal power present in the digital waveform ("quantization noise") is spectrally shaped to lie out of the signal band of interest, and can be separated with a bandpass filter. Band-pass delta-sigma modulators can be implemented with analog or digital inputs. We have demonstrated the characteristics of the bandpass delta-sigma signals experimentally, by using computer generated digital data streams which were upconverted to microwave frequency (clock rate of 3.6GHz) using a digital data multiplexer. The resulting signals were shown to meet the ACPR requirements for IS-95 CDMA signals. These BPDS signals can in principle be used to drive a switching-mode amplifier with high efficiency. Currently we are designing switching-mode power amplifiers that are optimized for this application. In the first iteration, we demonstrated amplifiers of this type that operate at low frequency (an output frequency of 10MHz) and achieve efficiency of 50%.

(9) High Efficiency S-Band Class-AB Push-Pull Power Amplifier

A novel high-efficiency S-band class-AB push-pull power amplifier was developed with broadband tuning of the second and third harmonics in the microwave power amplifiers based on a novel photonic band-gap (PBG) structure. It is well known that the PBG ground

plane for microstrip line provides low-loss, slow-wave propagation at lower frequencies, and a wide, distinctive stop-band as the frequency increases.

The maximum measured PAE is 63.8% at output power of 28.2 dBm. The measured PAE is better than 50% over a range of 3.47 GHz to 3.67 GHz. We observe significantly low harmonic power levels over a broad frequency range due to the filtering effects of the PBG ground plane. At 3.55 GHz, the measured second harmonic and third harmonic levels are 70 and 63 dB below the power level at the fundamental, respectively. A two-tone test has shown that the measured IP3 point is about 17 dB above the P1dB point. These results indicate that this compact push-pull power amplifier with PBG ground plane can simultaneously achieve excellent performance in terms of linearity as well as efficiency.

(10) Uniplanar Compact PBG (UC-PBG) Applications

UC-PBG invented at UCLA is considered most suitable for microwave planar circuit applications due to its uniplanar nature and its compact size with easy fabrication requirement. A number of applications have previously reported including slow-wave structures (delay lines), spurious-free bandpass filters, harmonic filters for class F amplifiers, and high efficiency planar antennas. Recently, we have studied the wave propagation characteristics of the coupled microstrip lines on the UC-PBG ground plane. In the slow wave region (frequencies below the stopband), the structure provides an enhanced effective permittivity. Therefore, the characteristics of the even and odd modes supported by a coupled microstrip lines are significantly different so that the degree of coupling can be made much higher than the coupled microstrip lines on a conventional substrate. This phenomenon has been numerically computed. It is therefore expected that a physically very short directional forward coupler can be realized. Based on the numerical analysis, design data have been constructed from which a physical prototype 3-dB forward coupler has been fabricated and tested. The results confirmed our prediction.

(11) Active Retrodirective Arrays for Wireless Sensor System

A reconfigurable retrodirective/direct downconversion receiver array for wireless sensor systems has been developed. The system operates at the 5.8 GHz ISM band. The compact circuitry serves as both a phase-conjugator and a direct conversion receiver and can be reconfigured simply by changing the LO frequency. With a LO at 2.9 GHz, which is half the RF frequency, the array works as a direct conversion receiver array, direct-downconverting the received signals and storing the demodulated information into memory. As soon as an interrogator sends a pilot signal to the array, the circuitry is switched into the phase-conjugating mode, and the array starts working as a retrodirective transponder, modulating and phase-conjugating the received pilot signal with the stored data.

A four-element prototype array has been fabricated and measured. In the direct downconversion

receiver mode, the measured circuit gain is about 7dB. A 2Mbps QPSK signal is successfully recovered by the direct conversion circuitry. E_b/N_0 for $BER=10^{-4}$ is approximately 12 dB without any error correction. In the retrodirective array mode, the circuit achieves RF-IF isolation of 20 dB and gain of 20 dB. By cascading amplifiers at output port, the phase-conjugated signal can be amplified more depending on the communication distance while maintaining the RF-IF isolation. The conversion gain is fairly flat and the RF-IF isolation stays below -10 dB over a RF range of 5.7GHz-5.9GHz. The monostatic radar cross section pattern of the four element prototype array shows the omni-directional characteristic of the retrodirective array.

The proposed system should find a wide variety of applications such as wireless sensor servers. By applying time division duplexing (TDD) and improving the baseband circuitry, it can also be used for other digital mobile communications such as wireless local networks (LAN).

(12) SIMPOL (Silicon/Metal/Polyimide) Multilayer RF Interconnects

In order to explore the feasibility of millimeter-wave circuits using the SIMPOL structure, two example circuits were designed and fabricated. A branch line coupler has been designed to produce in-phase and quadrature outputs at 37GHz. By defining the bandwidth of the coupler as where two outputs have relative magnitude differences less than 0.1dB, the measured bandwidth is 8.58GHz at the center frequency of 36.16GHz. At this frequency, the designed hybrid shows a very good matching in the power delivered to ports 2 and 3. These are measured to be -3.77dB and -3.75dB, respectively.

A multilayer ring resonator filter was designed at 2.4 GHz. It is a model for a SIMPOL implementation at 37 GHz. The filter exploits the multilayer capability available with SIMPOL. It consists of two coupled, dual-mode stripline ring resonators. The dual mode filters promise low loss, narrow bandwidth, and high Q. Additionally, they are very compact, measuring only a quarter-wavelength across the ring. Coupling between the resonators produces two additional poles per added resonator. Therefore a compact, 4-pole filter is realized by broadside coupling between two planar, dual-mode resonators over the same area. A unique feed design suppresses the second passband of the filter. With a rejected second passband, the upper stopband is extended over a wider bandwidth, for improved performance. The prototype was fabricated in three layers of RT/Duroid 5870 ($\epsilon_r = 2.33$), with ground plane spacing of $b = 91$ mil, and interconductor spacing of $S = 31$ mil. Figure 5 shows the filter response. The measured parameters of this filter are BW = 140 MHz centered at $f = 2.45$ GHz, with insertion loss of $|S_{21}| = 0.75$ dB. The lower stopband was below -20 dB, and the upper stopband was below -30 dB up to 5.35 GHz. The measured performance agrees very well with simulation. The 4-pole filter was fabricated in four layers of RT/Duroid 5870, with total substrate height of 124 mil, and spacing between the resonators of 31 mil. The measured parameters of this filter are BW = 260 MHz centered at $f = 2.42$ GHz, with insertion loss of $|S_{21}| = 0.57$ dB. This circuit is currently being scaled for implementation with SIMPOL at 37 GHz.

We have presented a novel interconnect concept for broadband silicon MMIC implementation. The prototype measurement results demonstrate that the SIMPOL structure is extremely effective in reducing the noise coupling between adjacent transmission lines ($<-80\text{dB}$ up to 18GHz and $<-40\text{dB}$ up to 50GHz). The insertion line loss is also very low ($<-0.25\text{dB/mm}$ up to 45GHz) with easily achievable thickness of polyimide layer ($27\mu\text{m}$). The successful application of the SIMPOL structure to a 37GHz branch line coupler indicates that this novel SIMPOL structure should provide an attractive solution for low-cost, high-performance wireless application up to millimeter-wave frequencies. Additional work on a compact low-loss 4-pole filter at 37GHz is currently being carried out to demonstrate the ability of the SIMPOL process to support multilayer planar structures.

3. List of Journal Publications

1. R. Y. Miyamoto, Y. Qian and T. Itoh, "Phase conjugator for active retrodirective array applications," *Electronics Letters*, Vol.36, No.q, pp.4-5, January 2000.
2. K. Mochizuki, R.J. Welty, P.M. Asbeck, "GaInP/GaAs C-up TC-HBT with zero-offset and low-knee-voltage characteristics", *Electronics Letters*, vol. 3, no. 3, Feb. 2000, pp. 264-265.
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4. W. R. Deal, N. Kaneda, J. Sor, Y. Qian and T. Itoh, "A new quasi-Yagi antenna for planar active antenna arrays," *IEEE Trans. Microwave Theory and Techniques*, Vol.48, No.6, pp.910-918, June 2000.

5. M. Iwamoto, A. Jayaraman, G. Hanington, P.F. Chen, A. Bellora, W. Thornton, L.E. Larson, P.M. Asbeck, "Bandpass Delta-Sigma Class-S Amplifier", *Electronics Letters*, vol 36 (12), pp.1010-1012, June 2000.
6. N. Guo and L.B. Milstein, "Uplink performance evaluation of multicode DS/CDMA systems in the presence of nonlinear distortions," *IEEE Journal on Selected Areas in Communications*, Vol. 18, No. 8, pp. 1418-1428, August 2000.
7. P. Ma, Y.F. Yang, P. Zampardi, R.T. Huang and M.F. Chang, "Modulating HBT's current gain by using externally biased on-ledge Schottky diode", *IEEE Electron Device Letters*, Vol.21, No.8, pp. 373-375, Aug. 2000.
8. X. Zhang, L.E.Larson, "Gain and phase error-free LINC transmitter", *IEEE Transactions on Vehicular Technology*, vol.49, (no.5), IEEE, Sept. 2000. p.1986-94.
9. P. Tseng, Liyang Zhang, G.B. Gao and M.F. Chang, "A 3-V Monolithic SiGe HBT Power Amplifier for Dual-Mode (CDMA/AMPS) Cellular Handset Applications", *IEEE Journal of Solid State Circuits*, Vol. 35, No. 9, pp. 1338-1344, Sept. 2000.
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12. K. Mochizuki, R.J. Welty, P.M. Asbeck, C.R. Lutz, R.E. Welser, S.J. Whitney and N. Pan, "GaInP/GaAs C-Up TC-HBTs: Optimization of fabrication process and epitaxial layer structure for high-efficiency high power amplifiers", *IEEE Transactions on Electron Devices*, vol. 47, no. 12, pp.2277-2283, Dec. 2000.
13. W. Xu and L.B. Milstein, "On the use of interference suppression to reduce intermodulation distortion in multicarrier CDMA systems," *IEEE Transactions on Communications*, Vol. 49, No. 1, pp. 130-141, January 2001.
14. X. Zhang, L.E. Larson, P.M. Asbeck, " Calibration scheme for LINC transmitter", *Electronics Letters*, vol.37, IEE, 1 March 2001. p.317-18.
15. C. Y. Hang, W. R. Deal, Y. Qian and T. Itoh, "High-efficiency push-pull power amplifier integrated with quasi-Yagi antenna," *IEEE Trans. Microwave Theory and Techniques*, Vol. 49, No. 6, Pt. 2, pp. 1155-1161, June 2001.

16. R. Y. Miyamoto, Y. Qian, and T. Itoh, "An Active Integrated Retrodirective Transponder for Remote Information Retrieval-on-Demand," to be published in IEEE Trans. Microwave Theory and Techniques, Vol. 49, No. 9, September 2001.

4. List of Conference Publications

1. J. D. Fredrick, Y. Qian and T. Itoh, "Low noise active integrated antennas for receivers," 2000 National Radio Science Meeting, Boulder, CO, p.65, January 2000.
2. Y. Qian and T. Itoh, "Novel planar photonic band gap structures for antenna applications," Millenium Conference on Antennas and Propag., 2A2-2, Dvaos, Switzerland, April 2000.
3. W. R. Deal, J. Sor, R. Y. Miyamoto, Y. Qian and T. Itoh, "A sixteen element quasi-Yagi antenna array with Chebyshev excitation coefficients," Millenium Conference on Antennas and Propag., 5A4-3, Davos, Switzerland, April 2000.
4. K. Mochizuki, R.J. Welty, P.M. Asbeck, C.R. Lutz, R.E. Welser, S.J. Whitney, N. Pan, Zero-offset low-knee-voltage GaInP/GaAs C-up TC-HBT for high-efficiency high power amplifiers, International Conference on Gallium-Arsenide Manufacturing Technology, Washington D.C., pp.169-172, May 2000.
5. C. Y. Hang, W. R. Deal, Y. Qian and T. Itoh, "Push-pull power amplifier integrated with quasi-Yagi antenna for power combining and harmonic tuning," 2000 IEEE MTT-S, International Microwave Symposium, Boston, MA, pp.533-536, June 2000.
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5. Book Chapter (Other than those in Wiley Book described below)

1. "CMOS Digital and Analog Building Block Circuits for Mixed Signal Applications", D. Pelhke and M. F. Chang, ULSI Devices, pp. 477-543, Edited by C.Y. Chang and S.M. Sze, Wiley and Interscience, 2000.

6. Awards and Recognition

1. Professor L. Milstein received *IEEE Communications Society Edwin Armstrong Achievement Award*, 2000.

2. Peter P. Asbeck was recognized as *Fellow of the IEEE*.
3. Ryan Y. Miyamoto, Ph.D. student at UCLA won the 2nd place in the *Student Paper Competition at MTT-S International Microwave Symposium*, held in Phoenix, AZ in May 2001.

7. Faculty Investigators

UCLA:

Professors T. Itoh (PI), K. L. Wang, M. F. Chang

UCSD:

Professors P. Asbeck, L. Milstein, L. Larson

8. List of Graduate Students and Post Docs

UCLA:

Ryan Y. Miyamoto (PhD), Cynthia Y. Hang (PhD), Chin-Chang Chang (PhD), Marc DeVincentis (MS), Sining Zhou (PhD), Liyang Zhang (PhD), Y. Qian (Post Doc)

UCSD:

Masaya Iwamoto (PhD), Rebecca Welty (PhD), Jeff Hinrichs (MS), Mahim Ranjan (MS), Jeff Keyzer (PhD), Xuejun Zhang (PhD), Robert Langridge (MS), P. Ma (Post Doc)

8. Technology Transfer

1. Concepts developed on this program served as the basis for a research contract with ONR, entitled Switching-Mode Microwave Amplifiers for Complex RF Signals.
2. Concepts developed on this program are part of a joint project with Rockwell Scientific and Kopin Corporation to develop improved HBTs for efficient power amplifiers.
3. Work on the Doherty amplifier has resulted in a research program with Intersil entitled Advanced Power Amplifier Architectures.
4. A book "**RF Technologies for Low Power Wireless Communications**" is published by Wiley Interscience. This book presents findings under support of the MURIs at UCLA/UCSD and at The University of Michigan. The table of contents follows:

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M. F. Chang and P. Asbeck
- Chapter 3. InP-Based Devices and Circuits
D. Pavlidis, D. Sawdai and G. Haddad
- Chapter 4. Si/SiGe HBT Technology for Low-Power Mobile Communication System Applications
L. Larson and M. F. Chang
- Chapter 5. Flicker Noise Reduction in GaN Field-Effect Transistors
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S. Pacheco and L. Katehi
- Chapter 11. Micromachined K-Band High-Q Resonators, Filters and Low Phase Noise Oscillators
A. Brown and G. Rebeiz
- Chapter 12. Transceiver Front-End Architectures Using Vibrating Micromechanical Signal Processors
C. Nguyen

Edited by T. Itoh, G. Haddad and J. Harvey

Attachment

A copy of Book "RF Technologies for Low Power Wireless Communications" will be sent under separate cover.